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Review

Intensification and spread of algal blooms over two decades in the coasts of India

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Abstract
Over the last two decades years, the Indian coastline has experienced a significant increase in marine microalgal blooms mainly *Noctiluca* sp. (Dinophyceae) and *Trichodesmium* sp. (Cyanophyceae). Some of these blooms are non-harmful. However, they can also be harmful leading to profound implications for marine ecosystem management, biodiversity conservation and sustainable use of marine resources. Environmental changes, nutrient availability and anthropogenic influences are some of the causes for these blooms while associated syndromes may include neurotoxic shellfish poisoning among others. In a recent study on the Arabian Sea and the Bay of Bengal, researchers looked at how different physicochemical parameters affect marine algal blooms including sea surface temperature, salinity and nutrient levels. The review gives insight into various types of algal blooms, what could cause them and their economic and public health implications. Therefore calls for continuous monitoring programmes to reduce negative impacts posed by harmful algal blooms on coastal resources and local economies. Additionally it explores spread or intensification patterns of algal bloom events; economic impact assessment for non-harmful bloom events on Indian fisheries sectors; satellite-based monitoring approaches for characterization phytoplankton bloom events etc., while underlining need for understanding these phenomena towards environmental health protection vis-à-vis sustainable development planning within Indian oceans management contexts.

Keywords Algae bloom · Harmful algae · Arabian sea · Bay of bengal · Coastal waters

1 Introduction

Marine water systems are often affected by algal blooms. These blooms are marked by rapid growth or accumulation of sizable populations of algae leading to water discoloration and impacts on the aquatic ecosystems [1, 2]. Nutrient pollution, high temperatures, dead organic material and large water masses are the main causes of algae blooms. Nutrient pollution especially from nitrogen and phosphorus sources like untreated industrial waste can cause eutrophication and increased growth of microalgae in aquatic systems [3, 4]. Hot temperatures which are getting worse due to global warming lead to faster decay of nutrients hence fuelling expansion of algal population [5]. In addition, dead plant debris within the water column serves as an ideal niche for proliferation of algal communities that further intensify blooming process. On the other hand, big volume oceans with few disturbances also help in the multiplication processes. Algal blooms have negative effects on both marine life and human beings; their consequences are enormous. Oxygen levels decrease greatly because these blooms take away oxygen making areas known as "dead zones" occur in areas of water

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where there is an absence of life for organisms [6]. Water contaminated by toxins released from cyanobacteria causing harmful algal blooms puts human health at risk and affects many aquatic organisms (freshwaters as well as marine environments). Furthermore there is a reduction in food available through fishery resources but more importantly poisons produced could result into illnesses even death upon consumption by animals or humans [7]. West coast, east coast alongside India experienced outbreaks caused by different species; among them *Cochlodinium polykrikoides, Karenia brevis, K. mikimotoi, Noctiluca scintillans, Trichodesmium erythraeum, T. thiebautii and Chattonella marina* [8]. Creating a direct impact on fisheries, marine life, and human beings including cases such as Paralytic Shellfish Poisoning (PSP) along its west coast due to this phenomenon [9].

This points towards a growing concern with an increase in occurrences from south to north along Indian coastline over the years. Protecting water quality and ecosystem health requires attempts to mitigate nutrient pollution besides addressing underlying causes of algal blooms. Regulations to limit nutrient inputs, like fertilizer and sewage discharge, can minimize algal growth and the occurrence of harmful blooms [10]. Thus, a proper understanding of the complex interplay between nutrient inflow, environmental drivers and development of algae is vital for the management as well as conservation of aquatic ecosystems [11]. Indian coastal regions are experiencing a rise in algal blooms which impact marine life, water quality and public health [12]. Historically, India has had problems with algal blooms, but reports indicate that there has been a significant increase in bloom occurrences. The west coast has experienced dinoflagellates dominated blooms while diatoms prevail on the east coast. These have resulted in mass fish mortalities signifying the ecological losses due to algal overgrowth within Indian waters [13]. Several policies and regulations have been developed to address this environmental issue. To monitor phytoplankton blooms across North India Ocean Region INCOIS (Indian National Centre for Ocean Information Services) established Algal Bloom Information Service (ABIS), Monitoring of HABs along the Indian coasts, a national coordinated multi–institutional research program on "HABs in the Indian EEZ" is being funded by Ministry of Earth Sciences (MOES) with Centre for Marine Living Resources and Ecology (CMLRE), CSIR–National Institute of Oceanography (NIO) is leading the Ballast Water Management Programme–India (BAMPI) which is supported by Directorate General of Shipping and Ministry of Shipping, India. Under this programme, Port Baseline Biological Surveys (PBBS), Indian Expendable Bathythermographic (XBT) programme funded by Ministry of Earth Sciences is in existence since early 2000. Remote sensing provides a synoptic tool for detection and monitoring of HABs on global scale. The algorithm is derived using Sea–viewing Wide Field–of–view Sensor (SeaWiFS) bands, and it is subsequently tuned to be applicable to Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua data. Indian National Centre for Ocean Information Services (INCOIS) has modified and adapted the Red Tide Indices. The main target groups for this service include fishermen researchers as well as environmentalists thus it focuses on creating awareness about harmful algal events at an early stage.

2 Algal blooms in India

2.1 Overview of algal blooms in India

Algal blooms have become a major environmental concern in India leading to adverse effects on aquatic ecosystems along with risk factors for human beings' health. Nourishment contamination through diverse means like agricultural run-off or industrial effluents caused bloom growth resulting in hypoxia with adverse human, animal health concerns and ecosystem complications [14]. Besides this researchers have developed an innovative tool which uses satellite data to trace cyanobacteria blooms within Indian inland water bodies. Over the past 20 years there has been an increase between 15% of Indian waters' harmful algal blooming severity [8, 15]. Various toxic microalgae have been identified by marine life experts inhabiting Indian waters signifying lethal consequences associated with such blooms for humans' health as well as marine ecosystems too [16]. They lead to harmful on marine life forms, water quality provision services together with fishery functions too. For example they cause depletion of oxygen level in the water blocking other organisms from accessing sunlight while also releasing toxins into the environment thereby affecting all aspects of an ecosystem at once [17]. High temperatures, slow moving water and the presence of dead organic matter are factors that accelerate the growth of algae. Different species, which include cyanobacteria, dinoflagellates and diatoms, can be responsible for harmful algal blooms in India whereby some have ability to produce toxins that can cause harm to other organisms [18]. For instance, *Gambierdiscus* sp., which is a dinoflagellate causing harmful algae blooms, while transferring toxins into higher trophic levels thereby leading to fish mortality together with toxicity. However diatom blooms are important for marine food chains but also harmful since there are times they produce toxin that leads poisoning among marine mammals and birds. Algal bloom information service has been developed in India towards curbing this environmental problem. The assists in detecting and monitoring blooms in the Indian seas by showing real-time information about the occurrence and spread of phytoplankton blooms. Areas where these blooms occur include North Eastern Arabian Sea; Coastal waters of Kerala; Gulf of Mannar; Coastal waters of Orissa [19].

The coast of the Indian peninsula is a place characterized by different kinds of algal blooms, which are to a large extent influenced by the meteorological conditions of the region. In particular, there are two oceans–Arabian (AS) and Bay of Bengal (BoB) that lay on both side of Indian coastline and whose seasonal reversal monsoonal winds blow from South West direction during May–September and from North East between November-January with transitions in between. The occurrence, dispersion, and magnitude of algal blooms within the area depend largely upon these winds. The coastal currents link AS to BOB whereby AS water with high salinity flows into BOB and vice versa [20, 21]. The AS has higher salinity due to excess evaporation, while the BOB receives a large freshwater influx from rivers, resulting in lower salinity. These hydrological conditions contribute to the occurrence of algal blooms in the two regions, which differ due to differences in surface temperatures. On the West Coast, algal blooms are caused by different types of algae, including diatoms, dinoflagellates, Cyanobacteria, Raphidophytes and Haptophytes. Dinoflagellates are the most common species that cause significant blooms affecting fisheries and human health. *Noctiluca scintillans* and *Trichodesmium erythraeum* are common bloom species that occur throughout the year with diatom blooms mainly in May and August-November and dinoflagellate blooms in September–October (Baliarsingh et al. [22]).

On the East coast *Asterionella japonica* is commonly seen among other bloom species like *N. scintillans* and *Trichodesmium erythraeum* (Table 1). The Tamil Nadu and Orissa coasts experience these kinds of blooms all-round the year, except for January and November. During the pre-monsoon period, the months of March to May typically experience a high incidence of maximum bloom cases [78]. Diatom blooms dominate this period compared to dinoflagellate blooms that prevail between April-August. Cyanobacterial blooms have been reported primarily in March- June. It should however be noted that there are both positive as well as negative consequences associated with algal bloom on marine life as well as human health. Some species kill fish leading to massive fish kills others may produce toxins harmful to people or other sea creatures [37]. Consequently; understanding such aspects unique meteorological characteristics like monsoon winds, seasonal variations, salinity levels and temperature difference is very important for monitoring events on algal blooming in Indian waters Effects reveal the importance of economic activity within Indian waters. Also highlighted is how these waters are ecologically vibrant. This article will briefly look at algal blooms and their impact on marine life as well as the need for research and networking in order to address the problem. It is important to note that there is a need for continuous monitoring, researching, and mitigating of the effects of algal bloom on the environment and aquatic life. Initiatives such as ABIS are important since they provide timely information that helps conserve marine ecosystems, fisheries and water quality (Table 1).

2.2 Hypoxic fish kills caused by harmful algal blooms in Indian waters

One of the most important issues in India's waters, are hypoxic and anoxic conditions and mass fish mortality events have been associated with these HABs that occur in India, particularly in its Arabian Sea. The death of fishes off the coasts of India has happened due to low oxygen occurrence linked with *Noctiluca scintillans* blooms [79]. Anoxic condition is a consequence of ammonia concentration during *Gonyaulax polygramma* bloom. Also, HABs increased in Arabian Sea due to bad water quality from land reclamation and urbanization [64]. These blooms cause oxygen depletion, shadowing sunlight and hypoxia dead zones which adversely affect marine life. This problem is one that concerns countries across Asia including India as they will have more coastal hypoxia/anoxia due to this reason. Indian waters can become anoxic through several interlinked processes that take place when algal blooms develop. Oxygen gets exhausted rapidly because there are too many algae growing during these blooms leading to formation of areas where there is no or very little air depriving aquatic creatures living there any chance of survival as they cannot live without sufficient levels of oxygen around them. This results in an imbalance within the aquatic ecosystem, leading to an overgrowth of algae. Subsequently, the decay of this excess algae further depletes oxygen levels, causing a deficiency in the aquatic environment. A case study involves a recent event that took place on 12th September 2019 where thousands of fish died along the coast of Gulf Mannar because low levels of O_2 was dissolved into water thus leading to the proliferation of *Noctiluca scintillans*. This phenomenon is a result of nutrient pollution and climate change, which leads to the growth of harmful algae that consume oxygen and create dead zones in the water [17]. The bloom decayed resulting into significant ammonia production, rapid decrease in dissolved oxygen and shock, stress as well as mass mortality of fishes [79]. Another one involved a change in water quality over time at Chunnambar backwater in Puducherry, with the most significant being the sudden

Table 1 Reporting of algae bloom in India from 2000 to 2024

Causative organism	Location	Period of occurrence	Region	Maximum abundance (cells/L)	Observation	Reference(s)
East coast						
Trichodesmium erythraeum	15°02′65′′N, 80°23′74′′E	June, 2000	Tamil Nadu	6.5×10^6	Discoloration of water surface	[23]
Noctilucla scintillans	–	June, 2000	Andaman and Nicobar Island	0.23	Light to vivid green discoloration of water	[24]
N. scintillans	–	July, 2000	Andaman and Nicobar Island	–	Greenish discoloration of water	[24]
T. erythraeum	11°N; 81°50′E 13°N; 80°42′E 19°44′N;89°04′E	April, 2001	Tamil Nadu	6.1×10^7	Discoloration of water surface	[23]
T. erythraeum	10° 58′ N 81°50′E	April, 2001	Pondicherry	–	Brownish patches on the water surface	[25]
T. erythraeum	19°44′ N 89°04′ E	April, 2001	West Bengal	–	Brownish patches on the water surface	[25]
N. scintillans	11°38.705 ′N; 92°42.513′E	December, 2002	Andaman and Nicobar Island	17×10^3	Green coloration of water surface	[26]
Asterionella japonica	19°16′ N 84°54′ E	March, 2004	Odisha	3.96×10^7	Dark brown patches on the water surface	[27]
N. scintillans	19°22′N 85°02′E	April, 2005	Odisha	2.38×10^5	Prominent red discoloration of surface water	[28]
T. erythraeum	12°33′ N 80° 11′ E	March, 2007	Tamil Nadu	4.14×10^6	Prominent red discoloration of surface water	[29]
N. scintillans	08° 35N-09° 25N 78° 08′ E to 79° 30″ E	October, 2008	Tamil Nadu	13.50×10^5	Dark green discoloration of water, death of several finfishes and shellfishes	[30]
T. erythraeum	12° 33′ N 80° 11′ E	February, 2008	Tamil Nadu	2.87×10^7	Discoloration of water surface	[31]
T. erythraeum	–	May, 2009	Andhra Pradesh	0.05×10^5	Visible patches on the water surface	[32]
Microcystis aeruginosa	1° 29′50"N 79° 46′24"E	December, 2009	Tamil Nadu	37.6×10^5	Green discoloration	[33]
T. erythraeum	10° 20′ N 79° 35′ E	May, 2011	Tamil Nadu	4.06×10^6	Deep saw like dust formation in surface water	[34]
T. erythraeum	11° 33′ 20″ N 92° 42′52″E	March, 2012	Andaman and Nicobar Island	270×10^5	Brownish to yellowish-brown discoloration on the water surface	[35]
Protoperidinium divergens	92° 43′56"N 11° 39′21"E	June, 2012	Andaman and Nicobar Island	335×10^5	Red and brown colour patches observed on the water surface	[36]
M. aeruginosa	12° 49′ N 80°15′E	June, 2012	Tamilnadu	6×10^8	Fish Kills incident	[37]

Table 1 (continued)

Causative organism	Location	Period of occurrence	Region	Maximum abundance (cells/L)	Observation	Reference(s)
T. erythraeum	11.676930° N; 92.734830° E to 11.677242° N; 92.746355° E	March, 2013	Andaman and Nicobar Island	14.56×10^6	Brownish discoloration on the water surface	[38]
T. erythraeum	–	April, 2013	Andaman and Nicobar Island	430×10^5	Pale brown to pinkish red discoloration of surface water, low fish catch	[39]
Chaetoceros tortissimum	11° 38′ N 92°40′ E	May, 2013	Andaman and Nicobar Island	$420–760 \times 10^5$	Green to dark green colored patches	[40]
Chlorella marina	8°46′374″N 78°09′477″E	August, 2013	Tamil Nadu	3.1×10^5	Greenish-yellow discoloration of water surface	[41]
N. scintillans	–	April, 2014	Odisha	3.3×10^5	Brown to dull-red discoloration of seawater, lack of fish in the affected area	[42]
Rhizosolenia alata	–	June, 2014	Tamil Nadu	1.62×10^5	Pale green discoloration of water surface	[43]
A. japonica	–	January, 2015	Tamil Nadu	563×10^5	A brownish discoloration of water	[44]
Rhizosolenia imbricata	–	January, 2016	Andaman and Nicobar Island	24,000 colony/L	Greenish patches	[45]
Gonyaulax polygramma	–	May, 2016	Odisha	$1.62 \pm 0.8 \times 10^4$	pinkish-red discoloration of near shore water	[46]
N. scintillans	–	August, 2019	Tamil Nadu	19,000 cells/L	brick red-colored patches on the sea	[47]
G. polygramma	–	October, 2022	Tamil Nadu	36.9×10^4	–	[48]
N. scintillans	–	October, 2022	Tamil Nadu	1.56×10^4	sea water turned green and fish died	[48]
Protoperidinium steinii	12.510706°N, 80.160174°E	October, 2019	Tamil Nadu	113.9×104	The brownish-red bloom appeared	[49]
Diatoma vulgaris	12°59′28.5″N 74°47′28.3″E	May, 2022	Karnataka	1.20×10^5	–	[50]
Phaeocystis sp	–	December, 2022	Odisha	–	Gelatinous globe-shaped substances floating in the upper layer	https://timesofindia.indiatimes.com/city/kolkata/algae-bloom-puts-fishing-at-risk-on-west-bengal-coast-threatens-to-disrupt-marine-ecosystem/articleshow/97238455.cms

Table 1 (continued)

Causative organism	Location	Period of occurrence	Region	Maximum abundance (cells/L)	Observation	Reference(s)
N. scintillans	–	November, 2023	Tamil Nadu	–	sea water turned green and fish died	https://www.newindianexpress.com/states/tamil-nadu/2023/Nov/08/algal-bloom-wiping-out-marine-life-in-thoothukudi-2630980.html
West coast						
T. thiebautii	–	December, 2000	Gujarat, Maharashtra, Goa	–	Discoloration of water surfaces	[51]
N. scintillans	–	March, 2000	Maharashtra, Gujarat	30×10^5	Yellowish-green mat over the water surface	[52]
T. erythraeum	15.84′N, 73.55′E	March, 2002	Goa	0.73×10^5	Visible patches on the water surface	[53]
Trichodesmium sp.	8.5 to 71.5°E 20 to 23°N	April, 2002	Gujarat	–	Dark brown coloration of the surface water with an appearance in the form of a sawdust spray	[54]
C. marina	–	September, 2002	Kerala	1.28×10^7	Reddish discoloration of water with slimy nature, foul smell, mass mortality of fishes, and mussels	[55]
N. scintillans	–	August, 2003	Kerala	1.02×10^7	Golden-yellow colored water surface, low fish catch	[55]
Karenia mikimotoi	8° 22′ N -8° 34′ N 76°48′ E—76°59′ E	September, 2004	Kerala	9.0×10^4	Mass mortality of fish, noxious odour and respiratory problems among children along the coast	[56]
Cochlodinium sp.		September, 2004	Kerala	9.8×10^4	Dirty-yellow discoloration	[57]
Gonyaulax diegensis	–	September, 2004	Kerala	–	Fish mortality due to clogging of gills, an emanation of noxious odour, respiratory disorder recorded mainly among children	[58]

Table 1 (continued)

Causative organism	Location	Period of occurrence	Region	Maximum abundance (cells/L)	Observation	Reference(s)
Helladosphaera sp.	–	September, 2004	Kerala	1,800,000 cells per litre	Strong stench felt up to 5 km from the coast. Over 200 children, mostly below 15 years, complained of nausea, chest pain, and short periods of breathlessness. Many were hospitalized	[59]
N. scintillans	8° 22′ N and 8° 34′ N and 76° 48′ E and 76° 59′ E	November 2004	Kerala	19.37×10^4	Massive mortality of fish, an emanation of noxious odour, and respiratory problems among the children on the coastal stretch	[60]
T. erythraeum	12° 59′N and 74° 31′E	May, 2005	Kerala	3.6×10^5	Extensive greenish-yellow to brownish patches on the water surface	[61]
Coscinodiscus asteromphalus var. *centralis*	–	August, 2006	Kerala	113.9×10^4	Conspicuous discoloration of surface water	[62]
N. scintillans	19°–24° N, 60°–64° E	March, 2007	Gujarat	1080–2542 cells/l^-	Intense green discoloration of water surface	[63]
Protoperidinium sp.	–	October, 2008	Karnataka	5000×10^5	Loose patches of cells appear on the water surface	[62]
G. polygramma		October, 2008	Karnataka	5×10^8	Reddish-brown discoloration of water	[64]
T. erythraeum	08°59.492 N, 75°59.334 E	May, 2009	Kerala	1.14×10^6	Pale brown to pinkish red water discoloration	[65]
Chaetoceros spp.	–	May 2009	Kerala	4.90×10^5	Off white discoloration	[66]
R. alata	1°59.471 N, 75°03.446 E	September, 2009	Kerala	4×10^3	Pale green discoloration of the sea surface	[67]
Trichodesmium sp.	–	Pre-Monsoon, 2010	Karnataka	–	Sawdust-like particles on the water surface	[68]
G. polygramma	–	October, 2010	Karnataka	5000 cells/L	Water Discoloration	haedat.iode.org/viewEvent.php?eventID=4450

Table 1 (continued)

Causative organism	Location	Period of occurrence	Region	Maximum abundance (cells/L)	Observation	Reference(s)
C. marina	11°42′18″N, 75°32′36″E	November, 2011	Kerala	45×10^6	Brownish coloration of the surface water and the low catch of economic fishes	[69]
N. scintillans	22°8″N, 21°8″N and 18°8″N latitudes in NEAS	April, 2012	Gujarat	3.5×10^6	A thick patch of bloom on the water surface	[70]
Trichodesmium sp.	9° 57′ 52″N; 75°50′38″E	April, 2012	Kerala	–	Prominent discoloration	[71]
G. polygramma	–	September, 2013	Kerala	780,000 cells/L	Brownish surface water discolouration	haedat.iode.org/viewEvent.php?eventID=4455
Leptocylindrus sp.	N 09° 56 50–09° 55 13; E 076° 10 43–076° 03 34	November, 2014	Kerala	$10.43–18.51 \times 10^5$	Discoloration of surface, filaments formed closely	[72]
N. scintillans	–	February, 2015	Gujarat	0.01×10^5	Green discoloration of surface water	[73]
Gambierdiscus sp.	–	June, 2015	Karnataka	–	Two individuals developed suspected ciguatera poisoning after consuming *Lutjanus bohar* purchased local market. High levels of CTX were detected by mouse assay in the implicated fish. Mice showed typical symptoms of CTX poisoning	[74]
K. mikimotoi		August, 2015	Kerala	11.9×10^5	High concentration and Water Discoloration	haedat.iode.org/viewEvent.php?eventID=7185
N. scintillans	09°55′ to 09°57′N and 75°59′ to 76°03′E	August, 2016	Kerala	4.73×10^5	Reddish discoloration of surface water	[75]
N. scintillans	10° 33′ 9.4932″ N and 76° 0′ 57.0708″ E	September, 2016	Kerala	7.5×10^5	Reddish discoloration of water and bioluminescence at night	[76]
N. scintillans	–	February, 2018	Gujarat	–	Water Discoloration	haedat.iode.org/viewEvent.php?eventID=7184

Table 1 (continued)

Causative organism	Location	Period of occurrence	Region	Maximum abundance (cells/L)	Observation	Reference(s)
N. scintillans	–	May, 2018	Maharashtra	–	Fish Mortality	https://timesofindia.indiatimes.com/city/mumbai/algae-bloom-leading-to-fish-deaths-off-mumbai/articleshow/64022880.cms
Gymnodinium sp.	–	June, 2018	Gujarat	–	Reddish discoloration of surface water	[77]

mass fish kill that corresponded with *Pseudo-nitzschia* bloom. In September 25th 2019, there was a mass fish kill event, has resulted into the growth of harmful algae that consume oxygen and create dead zones in the water [47]. On two occasions, *Karenia mikimotoi* had a harmful bloom producing hypoxic conditions on water as well as obstructing gill lamellae leading to asphyxia and fish death. This includes both economic species which were killed as well as livelihoods for local fishermen who were affected by H_2S concentration reaching up to1.6 mg L^{-1} following biomass decomposition at the end of bloom cycle [80]. Algal blooms disrupt other organisms' supply of oxygen and sunlight causing a disruption within marine food chain itself. Oxygen production and consumption balance may be disrupted, leading to anoxia in which the oxygen levels in water get very low putting the marine life at risk. HABs can bring about hypoxia through a complicated process that involves nutrient pollution and subsequent algal growth in India. These blooms illustrate the need for monitoring and managing nutrient inputs so as to prevent damage caused by excessive growth of harmful algae on water quality and biological diversity.

2.3 Causes and consequences of algal blooms in India

Globally, algal blooms are becoming an increasingly serious issue, and India is no exception. The causes and effects of algal blooms in India are many faceted, influenced by various factors that enhance their distribution and escalation. Algal blooms formation is a part of the climate change affecting marine ecosystems globally. Increase in temperature, changes in rainfall patterns as well as variations in nutrient levels and water quality remains one of the major reasons for the spread of harmful algal blooms [81]. These changes result into favourable conditions for algal bloom development resulting from climate change in India among other regions worldwide. Climate change has resulted to warming oceans, acidification as well as deoxygenating that enhances the growth of harmful species of algae. In turn, this upsets ecological balance thus impacting other organisms found within aquatic environments. It has been documented that recurring microalgae blooms have a profound impact on ecological goods and services provided by the Indian marine environment affecting over 200 million people and earning almost $7 billion annually [8]. Some of these impacts include mass mortality events among aquatic fauna due to HABs, human intoxication outbreaks, shellfish poisoning cases as well economic ramifications like reduced demand for products from affected areas or closure of shellfisheries. The Indian peninsula region also has some specific physicochemical parameters triggering marine algal bloom formation according to research conducted. Highly elevated sea surface temperature (SST), salinity plus nutrient supply stand out as crucial elements behind different microalgal bloom types. For example increased SST and salinity affect *Trichodesmium* sp. blooms while eutrophication prey abundance are causes for *Noctiluca* sp. Moreover, various syndromes such as neurotoxic shellfish poisoning, paralytic shellfish poisoning, among others are associated with harmful algal blooms like NSP and PSP. Hence, this leads to reduced demand for products and closings of shellfisheries or desalinization plants that result in significant revenue losses. So there is need for ongoing monitoring programs to reduce or eliminate the impacts of harmful algal blooms on coastal resources, local economies, and public health. Therefore understanding the environmental factors that drive HABs to manage environmental health better is important. These habitats are quite vulnerable due to their shallow nature and high susceptibility to fluctuating environmental conditions.

The Arabian Sea (AS) and the Bay of Bengal (BOB) exhibit significant hydrographic differences, leading to separate reporting of algal blooms on India's east and west coasts. Blooms occurring on the West Coast during different periods of the year—February-May, June–September, and October-January—are categorized as pre-monsoon (PrM), southwest monsoon (SWM), and post-monsoon (PoM) periods based on their seasonal occurrence. On the other hand, blooms occurring on the east coast during the same periods, along with the north-east monsoon (NEM) period of December-January, are categorized as PrM, SWM, PoM, and NEM. The distribution of nutrients, temperature, salinity, and currents in these regions is influenced by the hydrographic differences between the AS and BOB, affecting marine life's biodiversity and productivity. The BOB is characterized by low-density freshwater plumes on its surface originating from rivers and precipitation, creating distinct hydrographic features [13].

In contrast, the AS exhibits different hydrographic patterns, with unique mixed layer depth definitions used to compare the hydrography of the AS and BOB. The circulation patterns and salinity levels in the BOB differ from those in the AS, with observations of low-salinity surface water at the mouth of the Bay of Bengal extending towards the Arabian Sea and off Sumatra via Sri Lanka. These differences in salinity and water characteristics contribute to the distinct hydrographic conditions between the two regions. Changes in temperature, salinity, and nutrient levels affect the distribution and abundance of marine organisms, impacting the food web and overall ecosystem balance. The hydrographic conditions also influence the movement of marine species, migration patterns, and breeding grounds, all of which are essential for the sustainability of marine life in the AS and BOB regions. The prevalence of different types of phytoplankton species in response to the hydrographic features contributes to the overall health and dynamics of the marine ecosystem. The PrM period is marked with several algal bloom cases, among which cyanobacteria blooms (*Trichodesmium*) are the most common. These blooms have a well-defined periodicity and annual rhythm between February and May and can be described as seasonal. The AS is one of the most highly productive regions of the world ocean, undergoing periods of solid upwelling during monsoon and delivering cold, nutrient-rich waters from bottom depths. As a result, upwelling coupled with monsoons leads to high nutrient conditions that trigger high primary production [82]. During the monsoon season, the diatom and dinoflagellates communities and shifts in species dominance have been observed. However, blooms occur less frequently during this period, possibly due to phytoplankton's non-efficient utilization of nutrients under low irradiance due to monsoonal cloud cover. The PrM and PoM conditions provide favourable conditions such as bright sunlight, warmer waters, and nutrient input from rainfall and upwelled waters for phytoplankton species to proliferate and result in bloom formation [44]. The frequency of *Noctiluca* blooms is high from August to October, coinciding with the end of the upwelling season and usually preceded by a diatom bloom [22].

The BOB has unique characteristic features such as a large volume of freshwater input from river discharge and rainfall, warmer sea surface temperatures, monsoonal clouds, and reversal of currents. The low biological productivity of BOB has been speculated to be due to various reasons such as a narrow shelf, cloud cover during the summer monsoon, turbidity resulting from sediment influx, and fresh water-induced stratification. In BOB, most bloom cases are reported during the PrM, dominated mainly by diatom and cyanobacterial blooms. Among diatom blooms, *Asterionella japonica* is the most abundant bloom-forming species on the east coast of India from March to May. Most cyanobacterial blooms (*Trichodesmium erythraeum*) are mainly observed during the PrM period. Freshwater input, precipitation, and circulation patterns influence the AS and BOB hydrographic characteristics, leading to distinct hydrographic conditions between the two regions. Understanding and monitoring these differences is crucial for effective conservation and management strategies to preserve the delicate balance of the marine ecosystems in the AS and BOB.

2.4 Impact of algal blooms on aquatic life

Algae blooms can occur when algae populations grow rapidly due to excessive nutrients supply like nitrogen and phosphorus. These blooms may be fuelled by warm temperatures and abundant light and they can have significant consequences on aquatic ecosystems. One of the major effects of algal blooms is the excessive growth of algae which consumes high amounts of dissolved oxygen in water [83]. This leads to deprivation of oxygen necessary for survival by aquatic life forms. Also, an overabundance of algae prevents sunlight from entering water disrupting photosynthesis that is an essential process for aquatic plants or organisms. Some species of these particular algal blooms produce toxins which are dangerous towards the aqua life. Some consequences include fish die-offs; depletion levels; secretions into water; others can cause actual harm not just inside but also outside ecosystems through affecting bio accumulative toxicity within food chains etcetera produced by certain algae types might affect a wide range of organisms in an ecosystem thus causing disturbances in food webs among other things leading unbalance between communities lower up pyramid because toxic events happen each year in many areas worldwide. Evidently, nutrient pollution is caused by an overabundance of phosphorus and nitrogen that enter water bodies from agricultural runoff, sewage, and atmospheric deposition [84]. Blooms fuelled by excessive supply nutrients allow rapid growth algae with cascading effects on organisms within the ecosystem. This situation may lead to loss of oxygen in the water column changes its clarity or turbidity condition such as invasions introduced species into ecosystems often resulting crashes populations those organisms originally lived there causing great loss biodiversity due competition among new specie(s) against native ones. However, when dark brown coloration appears in surface waters, it indicates that large amounts of algae have accumulated. This accumulation decreases the shallowness of the water. Consequently, this phenomenon can negatively impact the overall survival of entire communities within that ecosystem. Furthermore these can cause zones where no living creature can breathe normally because they take up all available leading huge losses fish other plants animals.

2.5 Economic impact of algal blooms

Harmful algal blooms (HABs) are a perplexing occurrence in the marine environment of India. Some of these factors are sea surface temperature, salinity, nutrient levels, eutrophication and anthropogenic influences. The significant driving forces for the formation of *Trichodesmium* blooms include high sea surface temperature and high salinity; while those for various microalgae classes like Prymnesiophyceae, Raphidophyceae, Bacillariophyceae and Dinophyceae is contributed by high nutrient levels such as nitrogen (NO_3-N), phosphorus (PO_4-P) and silica (SiO_4-Si) combined with low salinity.

Moreover, eutrophication as well as prey organisms' abundance are responsible for *Noctiluca* blooms. Increasing sea surface temperatures and anthropogenic influences around Indian peninsula could lead to more occurrences of microalgal blooms including HABs. The socioeconomic implications of algal blooms in India are significant and far-reaching, with substantial economic and public health impacts. Algal blooms can lead to disruptions of social and cultural practices, adverse effects on economies, closure of water-related industries, decreased tourism activities, increased water treatment costs, and adverse health effects. These blooms affect various sectors, including commercial fisheries, tourism, public health, recreational centers, and monitoring and management, leading to losses in private and public well-being. Harmful algal blooms have profound economic impacts on public health, commercial fisheries, recreation, tourism, environmental monitoring, and bloom management in India, with public health impacts being the most significant, followed by commercial fisheries and tourism. Therefore, monitoring and managing algal blooms effectively is crucial to mitigate their adverse impacts on various sectors and ensure sustainable development.

2.6 Spread and intensification of algal blooms in India

The study examined different types of phytoplankton species that caused blooms around the Indian peninsula and their relationship with physicochemical factors and nutrient levels. It was discovered that blooms of *Chlorella marina* and *Trichodesmium* were positively associated with high SST, salinity on the sea surface, but negatively with nutrients. The Cyanophyceae bloomers were positively associated with PO_4-P and SiO_4-Si. The Trebouxiophyceae blooms were closely related to water salinity than SST. The study also found that Bacillariophyceae, Prymnesiophyceae and Raphidophyceae blooms were mainly observed under lower water temperatures as well as reduced salinities but higher nutrient levels majorly NO3-N, PO4-P and SiO4-Si. Moreover, it was also indicated by the study that Dinophyceae taxa always bloomed during all seasons along the coast of India with dominance during south-west monsoon season (SWM) implying that water eutrophication plays a significant role. *Karenia* and *Cochlodinium* mostly occurred under high NO_3-N; PO_4-P while those of *Noctiluca, Gonyaulax* and *Protoperidinium* were recorded under low conditions. Most members in this taxon showed elevated SiO_4-Si concentration during their blooming event. For majority of Cyanophyceae (*Trichodesmium*), most blooms occurred under low NO3-N condition which is characteristic for diazotrophic organisms like this one. No matter how fast other competitors grow, nitrogen deficiency promotes its diazotrophy giving it competitive advantage over others. In such events there may be a requirement for increased growth metabolism hence resulting into increased levels of PO_4-P while certain cases may be associated with non-uptake leading to more supplies. Higher incidences of Cyanobacteria blooms in PrM, when SST and salinity were high, further proved the importance of these factors to its occurrence. Additionally, lower factor weights obtained for SST and salinity indicated that they had a weak influence on the distribution of Bacillariophyceae, Prymnesiophyceae and Raphidophyceae blooms. During these blooms are mostly reported in the SWM season, one can see clear evidence of eutrophication along the coast of India. Furthermore, their prevalence over recent decades might indicate an increase in eutrophication along Indian coastal areas because of population growth together with urbanization resulting industrial wastes plus agricultural runoff from sewage discharge.

Different factors such as seasonal upwelling, monsoonal forcing and nutrient-rich waters from high riverine discharges affect the spread and intensification of algal blooms in Indian waters. Massive fish mortality is one of the notable impacts of algal blooms on marine life. Different periods of bloom include pre-monsoon, south-west monsoon, post-monsoon and north-east monsoon. Algal blooms have caused 68 incidences along the west coast of India by various groups of phytoplankton with dinoflagellates having a higher occurrence than others causing direct or indirect effects on fisheries and human health. On the west coast, there are common blooming species *Noctiluca scintillans* and *Trichodesmium erythraeum* that occur at high prevalence especially along Kerala coast. These two regions differ in salinity, temperature, freshwater influx among other hydrological conditions within Arabian Sea and Bay of Bengal respectively. In comparison to east coast of India the bloom occurrences have been more pronounced on the west coast. Due to their erratic nature algal blooms in Indian waters need constant surveillance. For effective management strategies understanding why these happen is important Continuous monitoring is necessary because these blooms develop sporadically resulting from unknown causes. However, this report exclusively looked into HABs within Exclusive Economic Zone across India during 1998–2010 period alone. This study recorded 80 algal blooms during this timeframe, with dinoflagellates, cyanobacteria, and diatoms being the primary bloom-forming groups. The research highlights an increase in the frequency, intensity, and spatial coverage of HABs in the Indian EEZ over the past decade, underscoring the global phenomenon of HABs and their diverse impacts on marine ecosystems and human health. To sum up, these studies provide valuable insights into the occurrence and characteristics of algal blooms along the coasts of India, highlighting the causative species, environmental factors, and the escalating frequency of bloom events. The detailed analysis presented in these studies contributes to a better understanding of the dynamics of algal blooms in Indian waters and the implications for marine biodiversity and human activities in the region.

2.7 The significance of periodic phytoplankton bloom surveys

To understand ocean productivity, biogeography, phonology, and climate change; it is important to study phytoplankton blooms. Phytoplankton being the base of the marine food web supply oxygen and nutrients to the ocean ecosystem thus necessitating the need for these studies. This therefore calls for regular studies on phytoplankton blooms as a means of understanding ocean productivity, biogeography, phonology and climate change. The ocean being the home to all living organisms in water including fish, whales among other species depends on phytoplankton which acts as its basic food therefore the necessity of constant frequent studying of its existence [85]. This includes analysis of bloom dynamics that would help identify what drives primary production in oceans thus contributing towards management policies aimed at maintaining healthy oceans e.g., through reducing pollution and overfishing. In addition, such researches are key in identifying necessary factors required for managing marine ecosystems and predicting their future health. In this regard, studying these blooms can help identify major controlling factors for primary production in open seas that could be useful in designing strategies to promote sustainable use of our resources [86]. They also help scientists understand where different plankton species thrive by examining patterns within them such as location and composition. Therefore blooming investigations can provide knowledge about environmental drivers responsible for patchiness of pelagic communities across large spatial scales hence enabling prediction about alteration of global diversity patterns due to changing climate. It has been shown that changes in temperature or salt together with nutrient fluxes lead to shifts in phytoplankton composition throughout the coastal regions [87]. In view of this research effort should be put into making projections concerning impacts associated with the future global warming on marine ecosystem. For instance, as seawater becomes more acidic due to uptake of atmospheric CO_2 by oceans, different species may respond differently in terms of growth rate. Therefore by studying these blooms oceanographers can project how climate change could affect fish stocks and other marine resources providing a basis for developing measures that would help mitigate any negative effects phytoplankton bloom studies are crucial for understanding the ocean's productivity, phonology, biogeography and climate change. Hence this information is important in managing healthy oceans with respect to annual fish and mammal migrations. Accurate information about ocean health and productivity thus requires continuous monitoring of phytoplankton blooms.

2.8 Non-harmful or beneficial blooms in India

Millions of Indians depend on fisheries for their livelihood. However, sustainable fishing in India has been hindered by harmful algal blooms (HABs). This is as a matter of fact due to economic losses that are caused by these HABs through fish mortality. Since time immemorial, there have been non-harmful or beneficial algal blooms in Indian fisheries [16]. These blooms have no impact at all on the environment and also have different benefits. Let us then look at some few instances when Indian fisheries had none-destructive algal blooms. The occurrence of diatoms in Indian fisheries is common knowledge for being rich in oil, which makes them a potential source of biofuel. A case in point is the Bay of Bengal with increased zooplankton growth that resulted from Ganges and Brahmaputra rivers having more nutrient-rich water [88]. It should be noted that some fish species like hilsa, shad and pomfret among others have seen an increase in fish stocks because of such reasons. Thus, local fishing communities have witnessed improved catches and living standards in their areas as a result. In this regard, one can also take the example of phytoplankton and zooplankton growth in the Arabian Sea leading to increased number of small pelagic fish like sardines and mackerel respectively; therefore enabling both commercial fishing that aims to get cash while subsistence fishing whose main goal is getting food for self as well as family members. Grazing such enhancements lead to increase productivity within marine environments but especially concerning Bay of Bengal's nutrient rich waters increasing zooplankton production which has raised fish stocks. These harmless bloom will raise population of zooplankton and hence productivity at the entire marine ecosystem which therefore will be a benefit for fishing industry and overall health [85]. It should be remembered that these blooms are non-hazardous since they do not release any poisonous substances to either sea life or human beings but instead they act as food as well as providing nutrients to many marine organisms, thus helping to increase biodiversity and improve general health of this environment. Similarly diatoms are capable of producing high-value products like cosmetics, pharmaceuticals and nutraceuticals. These are some examples among others of non-harmful algal blooms found in Indian fisheries. Nitrogen fixation by cyanobacteria makes water quality better while prompting growth of other aquatic plants. The benefits originating from use of non-harmful algal blooms within Indian fisheries are several [89]. These include; serving as a source of fish feed thereby enhancing their growth rates and condition. Most significantly, these biofuels can replace fossil fuels thus minimizing pollution caused by them into the surrounding. Nowadays, algae have become economically viable due to its significant potential for production of useful products like cosmetics, drugs and nutraceuticals. Consequently, this is good news for Indian fisheries because it means more places where no harmful algal blooms are found; with both economy and nature being beneficiaries of that. However when these algal blooms appear vigilance needs to be exercised so that their effects could be prevented than becoming disastrous on environment or economy.

2.9 Satellite-based characterization of phytoplankton blooms

In the coastal waters of India, phytoplankton blooms have increased both in frequency and intensity leading to ecological disturbances and water quality deterioration [90]. An understanding of the long term trend in these blooms is important for developing effective monitoring strategies. Satellite remote sensing has proven useful for synoptic monitoring of phytoplankton blooms, therefore this study describes a comprehensive analysis of such bloom extent in Indian coastal waters using satellite data (MODIS-Aqua) [19]. The study identified nine recurrent bloom sites: Gopalpur, Kalapakkam, Gulf of Mannar, Palk Bay, Kochi, Vizhinjam, Mangalore and Goa. In other words, coastal waters in the eastern Arabian Sea (AS) showed a relatively high dynamic range of chl-a compared to those in the western Bay of Bengal (BoB). Bloom events were determined as daily chla estimates retrieved from satellite with a cut-off value set at 1 mg m^{-3} and 1.30 mg m^{-3} for east and west coasts respectively; these thresholds were obtained by quartile analysis on anomalies from daily climatology. In reality however over the long term both coasts experience an upward trend with higher frequency on the west coast. Matchup analysis showed efficient bloom detection by MODIS-Aqua while eastern AS Coastal water was found to have higher occurrence frequencies than other areas according to some researchers. This indicates that operational services related to algal bloom; potential fishing zones as it affects quantity and others should be improved. Diatom blooms are prevalent within north western BoB's coastal area [91, 92]. This study aimed at assessing the long-term trend in distribution diatoms sampled through ocean colour satellites within north western BoB's littoral zone. Diatom's temporal distribution had a bimodal pattern during which they thrived before/after monsoons seasons. This is because nutrient availability enhances and environmental conditions are more conducive for phytoplankton growth during and after monsoons seasons. Furthermore, this study supports that the availability of diatoms creates a favourable environment for heterotrophic *Noctiluca scintillans* blooms while *Trichodesmium* exudates as the best source of nutrients for diatom growth. Creating specific satellite retrieval algorithms for different species of developing phytoplankton and improving ocean colour sensors' spatio-temporal efficiency can deepen our knowledge about how blooms affect ecosystem functioning. The Algal Blooms events have been significant challenges in Indian Ocean region (IOR) causing marine ecosystems disruptions, fisheries losses, aquaculture failures and public health risks through toxin production and water quality deterioration. This research addresses the need for comprehensive monitoring solutions at broad spatial scales and considering the co-existence of multiple HAB species in optically complex waters in the region. Algal bloom information services (ABIS) are provided by Indian National Centre for Ocean Information Services within the Indian Ocean region. These developed algorithms were validated with Satellite Ocean colour imagery from Moderate Resolution Imaging Spectroradiometer (MODIS) data as well as reported algal bloom events. Consequently, this algorithm provides a detailed view on where algal blooms occur in the Indian Ocean. These algorithms greatly contribute to environmental monitoring efforts which include detection of algal blooms, assessment of water quality and surveillance of aquatic eco-systems. It is hoped that these findings would assist in predicting HAB transportation to enable generation of HAB risk alert bulletins. This work contributes significantly to addressing HAB problems experienced in Indian Ocean Research by emphasizing on remote sensing methodology role in environmental management and public health concerns.

NASA's PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) satellite mission has been designed to detect diverse types of blooms in the ocean including harmful algal blooms (HABs). The use of advanced ocean colour sensors by PACE would help it measure the colour of water in the ocean and this can be used as a clue for identifying different types of phytoplankton and algae blooms. It shall also help in monitoring the health status of marine ecosystems and giving early warnings about bloom-related threats such as human health and fisheries. The new Indian Oceansat-3 is a successor to OceanSat-1 and OceanSat-2 but carries three more ocean observing sensors; Ocean Colour Monitor (OCM-3), Sea Surface Temperature Monitor (SSTM) and Ku-Band scatterometer (SCAT-3). An example is the OCM-3 which is a 13-channel instrument with high signal-to-noise ratio that will improve day-to-day accuracies in monitoring phytoplankton, ocean carbon uptake, harmful algal bloom alerts, and climate studies. Another sensor on-board is the SSTM that provides ocean surface temperature which is one of many important parameters for monitoring coral reef health as well as providing alerts for coral bleaching. The Ku-Band scatterometer onboard EOS-6 provides high resolution wind vector (speed and direction) data important for sailors or assimilation into ocean models and weather prediction models to improve their accuracy. The presence of OCM-3 instrument on board Oceansat-3 makes it very useful for detecting phytoplankton blooms as well as HABs. The concentration of phytoplankton chlorophyll measured by OCM-3 gives clues about primary productivity within marine ecosystems. These zones are characterized by thriving phytoplankton blooms from October to December hence elevated levels Chlorophyll-a showing areas with high levels of productivity especially extra tropical oceanic zones and equatorial regions as shown by the OCM-3 data. OCM-3 data has been utilized to locate high-productivity oceanic areas in the extra tropical, equatorial and coastal upwelling zones along the west coasts of major continents such as Indian subcontinent, South America and Africa. Besides, there is also a SCAT-3 scatterometer on board Oceansat-3 that provides high-resolution global ocean surface wind speed and direction information. Diverse climatic influences determine marine currents' behaviour in addition to other factors such as biogeochemical cycles. The purpose of this data is to provide an understanding of how different types of land vegetation interact with varying oceanic biological productivity. Ultimately, both PACE and Oceansat-3 missions are aimed at monitoring various types of blooms within the oceans including phytoplankton blooms as well as HABs. On one hand, advanced ocean colour sensors help PACE in measuring the colour of seawater while on the other hand; OceanSat-3 uses OCM-3 instrument to measure concentration of phytoplankton chlorophyll. These two missions have provided useful information for monitoring marine ecosystems health as well as predicting impacts posed by blooms on human health and fisheries.

2.10 Technology in addressing algal blooms

Advanced remote sensing technologies such as satellite data acquisition and geospatial analysis have greatly improved the monitoring and management of algal blooms in marginal productive seas such as the Indian Ocean. As a result, these systems allow researchers to know where algae bloom will appear or migrate by combining real time environmental parameters and monitoring system records. In addition, cloud based data analysis platforms offer scalable solutions and efficient ways of processing large volumes of information related to algal blooms thus giving researchers an opportunity to understand how they change over time, identify possible causes for their occurrence and suggest appropriate responses that can be used to deal with blooming problems. Similarly, some good examples from other countries would help India to come up with effective strategies for fighting against algal blooms.

According to NASA groups who have developed a new tool called TROPOMI, it can detect algal blooms through thin clouds by measuring acceptable wavelengths of light being emitted by algae. The goal of CyAN is to provide early warning systems to identify harmful algal blooms in fresh water bodies across the United States which helps in better decision making on how they should be managed. Remote sensors, UAVs, and satellite technologies pointed out by Global Infrastructure Hub are used globally for monitoring water bodies targeted at checking for risks associated with algae thereby reducing costs while alerting people on real-time basis. For spatial–temporal assessment of harmful algae development purposes, India has taken steps towards technology driven alternatives like developing optical system by IIT Madras. The use of satellite data along with optical parameters gives a good idea about what constitutes an algal bloom density that assists fishery efforts and conservation attempts. There are several case studies worldwide showing successful management of algal blooms in coastal waters. By addressing key factors triggering harmful rapid growth such as excessive nutrient runoff, increasing temperatures and abnormal weather conditions; successful mitigation measures have been implemented. Dual nitrogen-phosphorus reduction approaches that stress the need for collaborative actions beyond management boundaries or jurisdictions have been employed. Reports from Asia–Pacific Economic Cooperation (APEC) and Intergovernmental Oceanographic Commission of UNESCO have described how these harmful algal blooms in coastal waters should be monitored and managed. Algal bloom monitoring, control and mitigation require ecosystem based management, decision support tools as well as indicators. For instance, France has shown considerable progress in managing HABs and improving water quality in coastal areas through advanced technologies and data-driven approaches. There are also adaptable modelling approaches that help detect toxic algal species besides innovative tools to aid classification thus support improved global management strategies for their blooms.

3 Conclusion

There is a big concern about the problem of algal blooms in India that necessitates a comprehensive approach to mitigate their adverse effect on marine life, water quality and human health. Technology such as satellite information and remote sensing can be applied to detect harmful algal blooms in water bodies at early stages. Causes, effects and dynamics of algal blooms including studying cyanobacteria harmful algal blooms (cHABs) could be understood through researches and awareness creation campaigns. The dangers of algae bloom may also become known to the public for example in inland waters that are essential for livelihoods and households. To avoid risks linked with detrimental blooms, strict water quality guidelines should be made and adhered to regarding monitoring algal toxins. Control measures towards harmful alga blooms involve chemical, mechanical, genetic, biological and environmental ways which collectively work efficiently together. Encouragement of interdisciplinary approach is important especially when it incorporates technology research policy as well as community involvement against this menace called harmful algae bloom (HAB). India can advance its marine ecosystems' health by taking multi-dimensional role comprising observation data collection generating knowledge base public policies working as well as collaborations. The research provides insights into the diverse harmful algal bloom (HAB) events, categorizing bloom species based on their impact on marine life and humans. It discusses the factors contributing to the increase in HAB frequency and intensity globally, including improved detection methods, species dispersal, climatic changes, and eutrophication. Given their extensive coastlines and diverse marine habitats, the study underscores the importance of understanding algal bloom scenarios in maritime countries like India. Moreover, the document presents detailed data on microalgae species recorded in India's Exclusive Economic Zone (EEZ), highlighting the prevalence of harmful species and their impact on aquatic life. The methodology used for data collection includes in situ observations, sampling techniques, and physicochemical parameter analysis. The results section outlines the species composition contributing to algal blooms during the study period, emphasizing the need for cause and effect analysis based on visible discoloration, aquatic life mortality, and toxicity to humans. In conclusion, the study sheds light on the complex dynamics of algal blooms in Indian waters, emphasizing the need for continued monitoring and research to understand the environmental factors driving bloom occurrences. The research underscores the significance of studying algal blooms to mitigate their adverse effects on marine ecosystems, fisheries, and human health.

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Declarations

Ethics approval and consent to participate Not applicable.

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